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Modelling the effects of climate and land-use change on the hydrochemistry and ecology of the River Wye (Wales)

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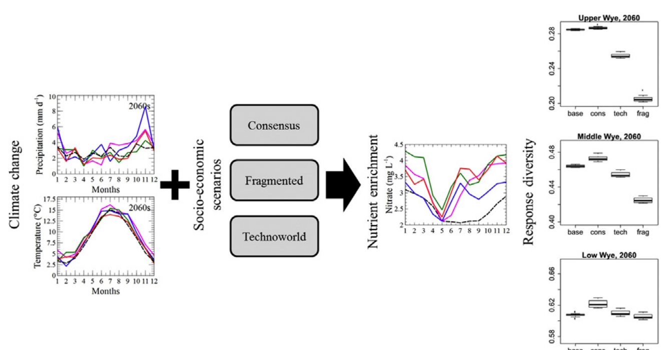
HIGHLIGHTS

- Socio-economic scenarios used to assess future changes in river nutrients and biota.
- Climate change expected to cause nutrient enrichment.
- Longitudinal position along the river mediates ecological response.
- Land-use change plays critical role in mitigation of climate change.

GRAPHICAL ABSTRACT



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ABSTRACT

Interactions between climate change and land use change might have substantial effects on aquatic ecosystems, but are still poorly understood. Using the Welsh River Wye as a case study, we linked models of water quality (Integrated Catchment - INCA) and climate (GFDL - Geophysical Fluid Dynamics Laboratory and IPSL - Institut Pierre Simon Laplace) under greenhouse gas scenarios (RCP4.5 and RCP8.5) to drive a bespoke ecosystem model that simulated the responses of aquatic organisms. The potential effects of economic and social development were also investigated using scenarios from the EU MARS project (Managing Aquatic Ecosystems and Water Resources under Multiple Stress). Longitudinal position along the river mediated response to increasing anthropogenic pressures. Upland locations appeared particularly sensitive to nutrient enrichment or potential re-acidification compared to lowland environments which are already eutrophic. These results can guide attempts to mitigate future impacts and reiterate the need for sensitive land management in upland, temperate environments which are likely to become increasingly important to water supply and biodiversity conservation as the effects of climate change intensify.

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1. Introduction

Reports from the Paris Agreement and the Intergovernmental Panel on Climate Change (IPCC) (Pachauri et al., 2014) have made clear the global significance of climate change driven by anthropogenic sources of carbon dioxide. The positive and negative impacts of climate change across the globe are still being considered and debated, but the potential changes in precipitation, temperature and sea level rise over the next century are likely to have important impacts on hydrology, water quality and ecology (Whitehead et al., 2009). The IPCC report considers the impacts of socioeconomic change superimposed on climate change, showing how socio-economic pathways (SSPs) will interact with climate change to generate a combined impact on people and livelihoods. This provides an integrated framework for addressing issues of change for national, regional and local governments and organizations to consider.

Previous studies have highlighted the importance of cross-sectorial approaches to assess the impacts of climate change on river water quality and ecosystems. For example, Palmer et al. (2009) pointed out the importance of collaborations among multiple partners and wise land use planning to minimize additional development in watersheds with valued rivers, stating that special attention should be given to diversifying and replicating habitats of special importance. Meyer et al. (1999) reviewed models that could be used to explore potential effects of climate change on freshwater ecosystems and discussed potential ecological risks, benefits, and costs of climate change. However, very few examples of integrate modelling approaches for the assessment of climate and land use change impacts on aquatic ecosystems and water quality exist in the literature.

The IPCC report and the EU Water Framework Directive (Chave, 2001; EU, 2000) have provided a backdrop to the MARS project (Managing Aquatic Ecosystems and Water Resources under Multiple Stress) funded by the European Union under the 7th Framework Programme (Hering et al., 2015). In any such study there is a need to understand the effects of multiple stressors on surface waters and groundwaters, their biota, and the ecosystem services they provide to people. River ecosystems are very likely to be affected by land-use or climate changes (Strayer and Dudgeon, 2010). Several studies have observed a reduction in diversity or abundance of river organisms in response to land-use (e.g., Gutiérrez-Cánovas et al., 2013), climate change (e.g., Durance and Ormerod, 2007) or anthropogenic disturbances (Ruhí et al., 2015). The reduction in river biodiversity is likely to reduce the capacity of these ecosystems to provide essential goods and services (Hooper et al., 2005) such as clean water.

As part of the MARS project, upland Wales has been investigated as a Northern Region that has been subject to much environmental change over the past 50 years (Durance and Ormerod, 2007; Whitehead et al., 1998a, 2009). Many of the upland headwaters in mid and southern Wales drain into large river systems and one of those is the River Wye (Fig. 1). In this study we evaluate the River Wye in terms of its hydrology, water quality and ecology and how these might change under a changing climate and changing socio-economic pressures. We utilise the INCA suite of models (Wade et al., 2002; Whitehead et al., 1998a) to quantify the change and use the model to simulate new future approaches to manage the environment.

2. The WYE catchment

The River Wye catchment is located in the Western Regions of the UK, in South and Mid- Wales, as shown in Fig. 1. It flows from Mid-Wales towards South-East Wales, reaching the River Severn estuary and the Bristol Channel at the town of Chepstow. Its catchment area is 4131 km^2. The catchment is included into the following coordinates (degrees latitude/longitude datum WGS84): N: 52.5, W: −3.8, S: 51.6, E: −2.4.The Rivers Lugg and the Monnow are its main tributaries, flowing into the main River Wye reach downstream of Hereford (Jarvie et al., 2005). The main land use is agriculture with livestock farming predominating in the north and west and more intensive arable farming in the south and east of the catchment. There is some industry based around the major towns (e.g. Monmouth and Chepstow). The upland areas of the catchment are generally used for rough grazing, while lowland areas support mixed and dairy-farming and horticulture (Oborne et al., 1980). The water quality of the River Wye is characterised by patterns of high winter concentrations of nitrate and

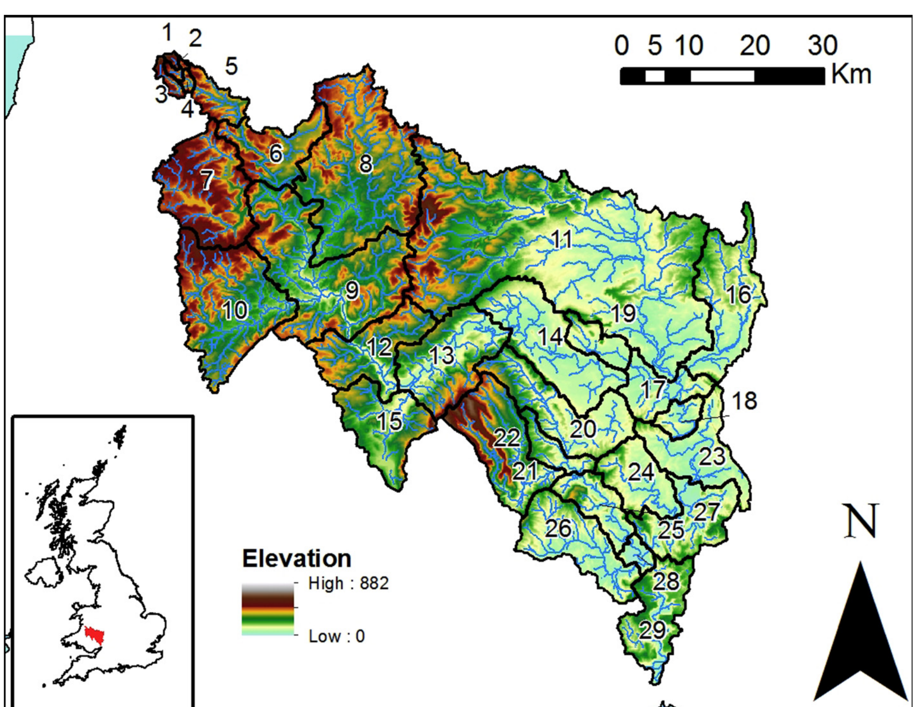

Fig. 1. The River Wye catchment and the INCA model sub-catchments.

low summer concentrations (Oborne et al., 1980), mainly related to agriculture and fertiliser usage.

The Wye catchment is rich in wildlife and habitats and this is recognised in the designation of the Wye and several tributaries as a riverine Special Area of Conservation. The area offers many opportunities for water-based recreation. The River Wye is a well-established and nationally significant salmon and brown trout rod fishery and also a locally important coarse fish fishery. Elver fishing also takes place within the tidal reaches of the Wye. The Elan Valley system of reservoirs (North-Western part of the catchment) is vital in providing water for Birmingham, Gloucestershire and South Wales. The local economy is moderately dependent on businesses requiring water abstraction, primarily agricultural, where trickle and spray irrigation is frequently used.

Daily water discharge time series have been retrieved from the National River Flow Archive (NRFA, http://nrfa.ceh.ac.uk/data/search). Several stream gauges can be found within the River Wye catchment (see Supplementary Material, Table S1). Nitrate and Ammonium data were obtained from the Centre for Ecology and Hydrology for eight locations within the River Wye catchment, collected from 2004 to 2009 with a monthly to fortnightly frequency, and used for model calibration. Data collected by the Environment Agency of England and Wales was also used for three locations, spanning from 1974 to 2012, and used for model validation (Simpson, 1980).

3. Methodology

3.1. The integrated catchment model (INCA)

The INCA model is a process-based model which simulates the main processes related with rainfall-runoff transformation and the cycle and fate of several compounds, such as nitrate, ammonium, carbon and phosphorus. The INCA Model has been developed over several years as a result of several research projects and is a dynamic computer model that predicts water quantity and quality in rivers and catchments. The primary aim of INCA is to provide a process-based representation of the factors and processes controlling flow and water quality dynamics in both the land and in-stream components of river catchments, whilst minimising data requirements and model structural complexity (Whitehead et al., 1998a, 1998b). As such, the INCA model produces daily estimates of discharge, and stream water quality concentrations and fluxes, at discrete points along a river's main channel. Also, the model is semi-distributed, so that spatial variations in land use and management can be taken into account. The hydrological and nutrient fluxes from different land use classes and sub-catchment boundaries are modelled simultaneously and information fed sequentially into a multi-reach river model. The INCA model was originally tested on 20 catchments in the UK for a variety of purposes (Crossman et al., 2013; Lu et al., 2016, 2017; Nizzetto et al., 2016; Whitehead et al., 2016), including catchments in Wales (Bussi et al., 2017b), and over 20 catchments across the EU and now 30 catchments around the world. The INCA model has also been tested for land-use and climate change impact assessment applications (Bussi et al., 2016a, 2016b).

The INCA model requires time series of Hydrological Effective Rainfall (HER) and Soil Moisture Deficit (SMD) as inputs, and these have to be produced by an independent hydrological model, which takes into account soil water retention and evapotranspiration. In this study, the PERSiST model was used (Futter et al., 2014), a simple and flexible hydrological model especially created to produce inputs for the INCA family of models. Precipitation and temperature data were taken from Met Office stations. Several stations exist within the Wye catchment, measuring daily meteorological variables. Given the topography of the catchment, with steep slopes and relatively large difference in altitude from the uplands to the lowlands, and the natural spatial variability of rainfall and temperature, a single station cannot provide exhaustive information about the precipitation falling on the catchment and the temperature over the whole catchment. For this reason, the average precipitation falling on the catchment and the average catchment temperature were determined, using information from several rain gauges spread all over the catchment. The mean temperature was calculated as the average between minimum and maximum temperature.

Spatially distributed information is required to estimate some of the INCA model parameters. The Ordnance Survey (OS) Terrain 50 was used as a digital elevation model. The digital elevation model was used to define the sub-catchment boundaries, and to calculate their areas and mean reach slope. The Land Cover Map 2007, released by the Centre of Ecology and Hydrology in 2011, was used to characterise the land uses in the catchment (Smith et al., 2007). The land cover categories were aggregated to six classes of land use: forest, short vegetation (ungrazed), short vegetation (grazed, non-fertilised), short vegetation (fertilised), arable and urban, following Jin et al. (2012). The proportion of land use for each sub-catchment is required by the INCA model. The River Wye catchment was divided into several sub-catchments (supplementary Material, Table S2). For each catchment, catchment area, reach length and land uses were defined.

The INCA model was calibrated over the time period 1/1/2004–31/10/2009 and validated over the time period 1960–2015, with a daily time step. The model parameters were manually adjusted to reproduce observed values of hydrological and water quality variables. In particular, observed values of water discharge were used to calibrate the hydrological model parameters (direct runoff residence time, soil water residence time, ground water residence time, threshold soil zone flow, rainfall excess proportion, maximum infiltration rate, discharge/velocity relationship coefficient and exponent) and observed values of nitrate concentration were used to calibrate the INCA model parameters (denitrification rate in soil and river, nitrification rate in soil and river, mineralisation rate in soil, immobilisation rate in soil, fertiliser addition rate in soil, plant uptake). Manual calibration has been proved as a robust method for obtaining acceptable simulations with the INCA family of models (Cremona et al., 2017) Furthermore, while Ledesma et al. (2012) performed a mixed automated and manual calibration, they also highlighted the importance of manual calibration for models and specifically for INCA. More complex calibration techniques have already been applied to the calibration of the INCA model (Bussi et al., 2017a, 2016a), but given the focus of this study and the goodness-of-fit of the results (presented in a following section), they were not employed in this study. Further research is needed to assess the influence of such techniques on the outcomes of the present paper.

3.2. Ecological modelling

In order to forecast the response of the biological communities of the River Wye to land-use and climate change scenarios, ecological models were built using biological and environmental data from 78 locations placed in Mid and North Wales. In those rivers, one sample of aquatic invertebrates was collected for each location in spring (March–April 2012–13) using kick-sampling (2-minute just in riffles) to characterise the biological communities. Invertebrate richness (number of invertebrate taxa) and response diversity (variety and range of biological traits to cope with disturbance based on functional richness, Villéger et al., 2008) were derived to quantify the response of these aquatic communities. Response traits included fuzzy coded traits such as number of generations per year, lifespan, reproduction mode, respiration type, resistance form and dispersal capacity (Tachet et al., 2010). For each invertebrate genus, we created a *taxa* × *traits* table where a number of affinity points (i.e. 3, 5, 7) were distributed across the categories of each trait, according to the frequency of occurrence within the genus. This way of gathering trait information is called fuzzy coded approach (Chevenet et al. 1994), and entails compiling the intraspecific biological information available for the species belonging to each genus (e.g., juvenile and adults, male and female, different species). Before analysing data, fuzzy coded data were converted to percentages of affinity for each trait. This procedure standardises the potential differences

in the codification scores (i.e. different initial number of affinity points). To estimate response diversity, we first computed a matrix containing the pair-wise functional dissimilarity across taxa, using Gower's index from the *taxa* × *traits* table (hereafter, Gower trait matrix) (Gower, 1971). Second, based on Gower trait matrix, we built a functional space through a Principal Coordinate Analysis (PCoA). This analysis reduces all trait categories to a few main axes (or coordinates), retaining a high proportion of cross-species variance, and represents taxa in the space defined by these main axes (Villéger et al., 2008). To select the number of relevant functional axes, we assessed the minimum number of dimensions (from two to 10) that provided a good representation of the original Gower trait matrix (Maire et al., 2015). We kept two dimensions (mean squared deviance, mSD = 0.009), which represented 31.5% of the original trait variation.

The main gradients of anthropogenic or natural environmental variation were also characterised, including annual pH, total oxidised nitrogen (TON), altitude (alt), precipitation of the wettest month (prec_max), geographical latitude (lat) and longitude (lon). TON was log-transformed to reduce distribution skewness. All the predictors were standardised to mean = 0 and SD = 1 to allow for within-model coefficient comparison in form of Standardised Effect Sizes (SES).

To assess the influence of the stressors, natural descriptions and their interactions on the biotic indicators, we adopted a multi-model inference procedure (Grueber et al., 2011), which is a useful method to quantify multi-stressor effects on biological communities (Feld et al., 2016). First, as global models, we fitted a Quasipoisson error distribution model for species richness and a generalised linear model with a Gaussian error distribution for response diversity. For each global model, pH, TON and the interaction pH x TON were included as stressors, and altitude, precipitation of the wettest month, latitude, longitude, and the interaction pH x latitude as descriptors of natural variability. Second, using the MuMIn R package (Bartoń, 2014), we fitted the models resulting from all possible predictor combinations included in the global model, which were ranked according to their Akaike Information Criterion (AIC) value, i.e. the model ranking first was the one minimising the AIC value. Third, the top models that differed in two AIC units or less (delta ≤ 2) from the model ranked first were retained, along with their model weights (probability of being the best model). Four, two final models were obtained by using a model averaging approach, where we derived a weighted mean of the coefficients from the top models where each predictor appeared, using model weights ('natural average', Burnham & Anderson, 2002). Also, for each of the top models, we checked residuals to assess the normality and homoscedasticity of their distributions. Ecological modelling was conducted using the R statistical software (RC Team, 2016).

3.3. Anthropogenic drivers

3.3.1. Socio-economic scenarios

Future socio-economic scenarios were implemented within the INCA model to simulate the impact of human-induced changes such as land-use change, population growth and agriculture intensification. These scenarios were based on the Shared Socioeconomic Pathways (SSPs) from Moss et al. (2010), van Vuuren et al. (2014), O'Neill et al. (2014) and Kriegler et al. (2014). The scenarios were downscaled in the MARS project in concert with the stakeholders, such that they represent likely and achievable futures (Cremona et al., 2017). Three scenarios were considered:

1. Consensus (based on SSP2). In this world, trends typical of recent decades continue, with some progress towards achieving development goals, reductions in resource and energy intensity at historic rates, and slowly decreasing fossil fuel dependency.
2. Fragmentation, or Fragmented World (based on SSP3). The world is separated into regions characterised by extreme poverty, pockets of moderate wealth and a bulk of countries that struggle to maintain living standards for a strongly growing population. Changes in pH were also considered, as very intense use of fossil energy (coal and unconventional sources) with absence of flue-gas desulphurisation technologies to reduce costs is foreseen. This would lead to a pervasive and large acid sulphur deposition, which decreases pH (2030: −0.50 pH units/2060: −0.75 pH units).
3. Technoworld (based on SSP5). This world stresses conventional development oriented towards economic growth as the solution to social and economic problems through the pursuit of enlightened self-interest. The preference for rapid conventional development leads to an energy system dominated by fossil fuels, resulting in high GHG emissions and challenges to mitigation. Lower socio-environmental challenges to adaptation result from attainment of human development goals, robust economic growth, highly engineered infrastructure with redundancy to minimize disruptions from extreme events, and highly managed ecosystems.

The socio-economic scenarios were implemented by changing some of the INCA model parameters in order to reproduce the impact of the different storylines, as indicated in Table 1. The baseline land uses are reported in the Supplementary Material, Table S2.

The socio-economic scenarios were implemented by changing some of the INCA model parameters in order to reproduce the impact of the different storylines, and in accordance with the guidelines of the MARS project. In particular, the consensus scenario was implemented in the following way: 10% of the forest area was turned into forest land; 30% of arable land was turned into grassland; the nitrogen fertiliser application was decreased by 50%; the growing season was extended two months due to climate change; the effluent flows were increased by 30% due to population growth. The fragmentation scenario was implemented in the following way: 5% of the forest area was turned into grassland; 15% of grassland was turned into arable land; the nitrogen fertiliser application was increased by 15%; the growing season was extended two months due to climate change; the effluent flows were increased by 30% due to population growth. The technoworld scenario was implemented in the following way: 10% of the forest area was turned into arable land; 30% of grassland was turned into arable land; the nitrogen fertiliser application was increased by 30%; the growing season was extended two months due to climate change; the effluent flows were increased by 30% due to population growth.

3.3.2. Climate change scenarios

In order to model the impact of climate change, future scenarios of precipitation and temperature are needed. These were obtained using

Table 1
Land-use change scenarios implemented in INCA.

Scenario	Consensus	Fragmentation	Technoworld
Forest land variations	10% of the forest area turned into arable land	5% of the forest area turned into grassland	10% of the forest area turned into arable land
Arable land variations	30% of arable land was into grassland	15% of grassland turned into arable land	30% of grassland was turned arable land
Fertiliser use variations	Nitrogen fertiliser application decreased by 50%	Nitrogen fertiliser application increased by 15%	Nitrogen fertiliser application increased by 30%
Growing season variations	Growing season extended two months due to climate change	Growing season extended two months due to climate change	Growing season extended two months due to climate change
Population growth	Effluent flows were increased by 30% due to population growth	Effluent flows were increased by 30% due to population growth	Effluent flows were increased by 30% due to population growth

two different global circulation models (GCMs): the GFDL (Geophysical Fluid Dynamics Laboratory) model, developed by the National Oceanic and Atmospheric Administration (NOAA, US) (Donner et al., 2011), and the IPSL (Institut Pierre Simon Laplace) model, developed by the IPSL Climate Modelling Centre (France) (Dufresne et al., 2013).

Daily precipitation and temperature, spatially averaged over the Wye catchments, were obtained from these two models forced by two different Representative Concentration Pathways (RCPs), or greenhouse gas concentration trajectories (Moss et al., 2008), the RCP4.5 and the RCP8.5. RCP4.5 describes a mean global warming of 1.4 (0.9 to 2.0) °C for 2046–2065, while RCP8.5 presents a global warming of 2.0 (1.4 to 2.6) °C for the same time period.

The climate model data were corrected in order to remove the model bias in reproducing past precipitation and temperature. In particular, a Delta Change approach was used to correct the bias of RCM (Regional climate models) scenarios to generate local climate scenarios. The approach is based upon transferring the monthly average change signal between RCM (regional climate model) control (2006–2010 in this case) and RCM scenario period to an observed time series (2006–2010 in this case). Three data series were used in the bias correction: (1) GCM control periods (2006–2010), (2) Baseline periods (2006–2010), and (3) GCM scenario period (2011–2099).

The scenario daily temperature ($T_{scen,\ d}$) was derived by adding the absolute monthly change signals to the observed time series. In the case of precipitation, the observed data were scaled with the relative change signals given by the RCM:

$$T_{scen,d} = T_{obs,d} + (TRCM_{scen,m} - TRCM_{con,m}) \quad (1)$$

$$P_{scen,d} = P_{obs,d} * \left(\frac{PRCM_{scen,m}}{PRCM_{con,m}}\right) \quad (2)$$

where $T_{obs,\ d}$ and $P_{obs,\ d}$ are observed daily temperature and precipitation, $TRCM_{con,\ m}$ and $PRCM_{con,\ m}$ are monthly average RCM temperature and precipitation of the control period, and $TRCM_{scen,\ m}$ and $PRCM_{scen,\ m}$ are monthly average RCM temperature and precipitation of the scenario period. The resulting time series of climate change-affected precipitation and temperature are summarised in Fig. 2.

Combinations of climate change scenarios and socio-economic scenarios were used to drive the INCA model and the ecology model, to obtain a wide range of possible future pathways. This approach has been used widely in the past (Herrero et al., 2017; Prudhomme and Davies, 2009; Ruiz-Villanueva et al., 2015), and although its limitations have also been clearly pointed out (Singh et al., 2014), it still provides meaningful results for impact and mitigation analysis.

4. Results

4.1. Model calibration

4.1.1. Flow and nitrate

The INCA model was calibrated and validated to reproduce both the observed flow and nitrate concentration at the stations indicated in the Supplementary Material, Table S2. The results are shown in Table 2, with calibration and validation performances shown in terms of Nash-Sutcliffe Efficiency (NSE, Nash and Sutcliffe, 1970) for the daily flow and in term of percent bias (PBIAS) for the nitrate concentration. Reproduction of observed flows was in general good or very good, apart from the station 2, located in the headwaters (catchment area around 10 km^2), where the model was able to reproduce the low flows but is underestimating the flood peaks (not shown). In terms of nitrate concentration, again the results were satisfactory (|PBIAS| < 20%) apart from station 2, where the calibration PBIAS was −53%.

Calibration results are also shown in Figs. 3, 4 and 5, where the daily time series of the modelled flows and nitrate concentrations are shown against the corresponding observed values for selected subcatchments.

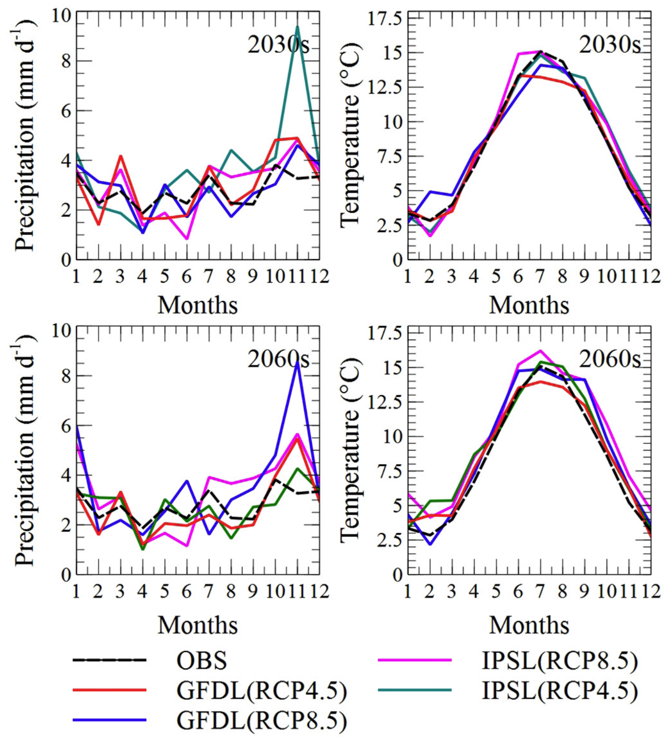

Fig. 2. Changes in precipitation and temperature forecasted by the climate models ("2030s" indicates the time period 2020–2050, "2060" indicates the time period 2050–2080).

While it is clear that the model reproduced the observed flow, some errors in the simulation of the nitrate concentration can be observed, although the general seasonal patterns were reproduced correctly. Nevertheless, given the uncertainty in both the processes and the nitrate measurements, the generic behaviour and the catchment response to climate and land-use changes, the performance of the model can be considered satisfactory.

It is relevant to remind that the measure of the goodness of fit of a model depends on the purposes of the model. In this study, the model will not be used for nitrate forecasting or daily-based nitrate modelling, but rather for assessing the long-term changes in average concentrations of nitrate in the river. For this reason, we assessed the model results using an average-based statistic such as the PBIAS. From this point of view, the model can be judged as fit for the purposes of this study.

Table 2
INCA model calibration and validation results.

		Calibration (2004–2009)		Validation (1960–2015)	
Stream	Station	NSE flow	PBIAS nitrate	NSE flow	PBIAS nitrate
Wye	2	0.22	−53%	0.19	−50%
Wye	6	–	–	0.60	–
Wye	9	0.77	−15%	0.79	–
Wye	12	–	−14%	–	–
Wye	14	0.82	–	0.73	−66%
Wye	17	0.61	–	–	–
Wye	27	–	19%	–	–
Wye	28	0.66	13%	0.79	−2%
Wye	29	–	18%	–	–
Llynfi	15	0.59	17%	0.56	–
Ieithon	8	0.60	–	0.64	–
Irfon	10	0.58	–	0.61	–
Mynwy	21	0.43	–	0.52	–

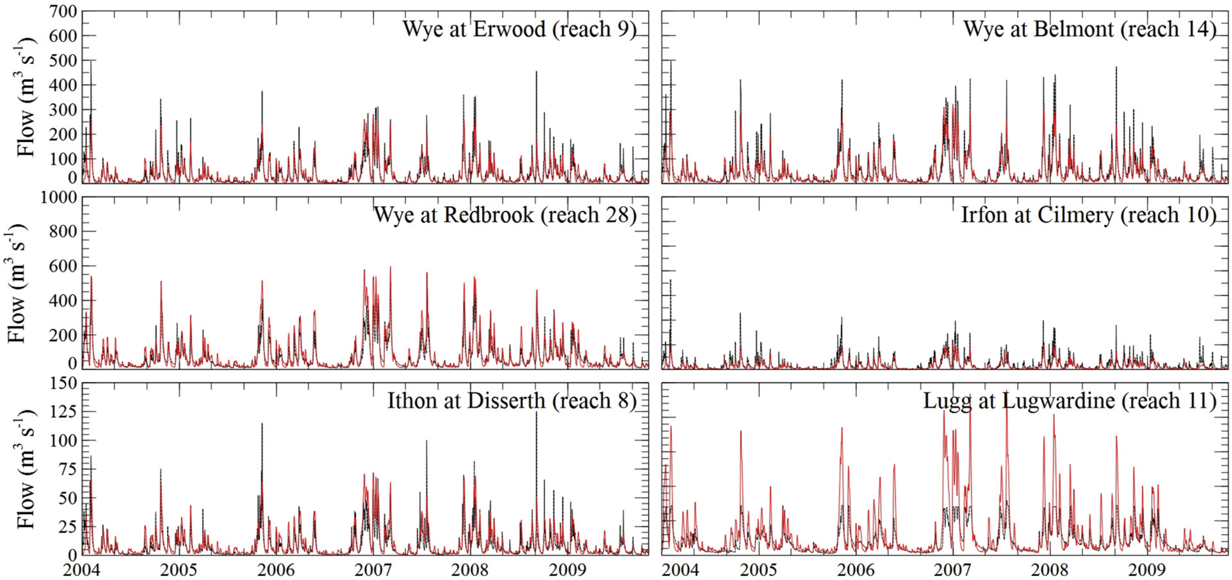

Fig. 3. INCA model results and observed flow at six sites along the Wye (2004–2009). Note that the stream gauge for the River Lugg does not measure flows above 35 m^3 s^{-1}. Red lines: model results. Black lines: measurements. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4.2. Climate change and land-use change impacts

4.2.1. Flow and nitrate

The impacts of climate change on the flows of the River Wye for the time period 2050–2079 (hereafter 2060s) are shown in Fig. 6. It is shown that the different combinations of climate model and RCP provided slightly different results. For example, the model GFDL, coupled with the RCP 8.5 indicated that little changes in hydrology should occur, in agreement with the results in Fig. 2, i.e. little changes in precipitation and temperature. Meanwhile, the model IPSL coupled with the RCP 4.5 forecasts an increase of 50–100% in autumn-early winter flows. The impacts of climate change on the nitrate concentration of the River Wye for 2060s are shown in Fig. 7. Nitrogen concentrations are expected to decrease in the consensus world for the middle and low Wye. However, for the fragmented and technoworld scenarios, models predicted a strong increase in nitrogen concentration for the upper and low Wye.

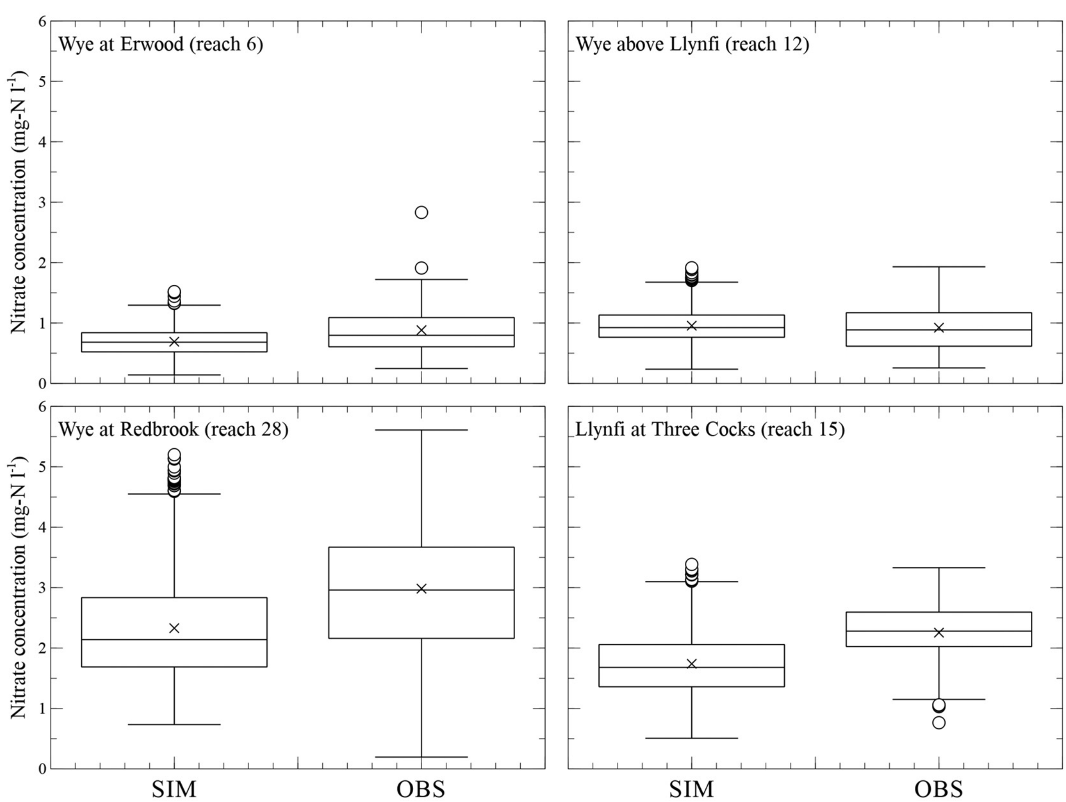

Fig. 4. INCA model results for Nitrate-N at six sites along the Wye (2004–2009).

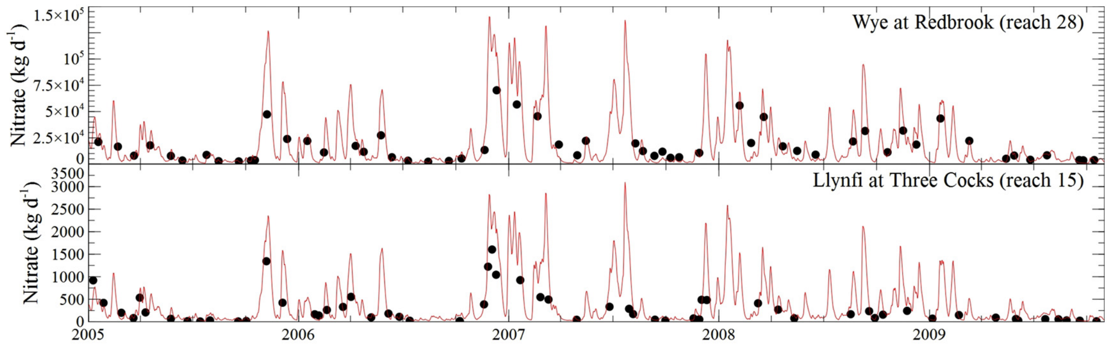

Fig. 5. INCA model results for nitrate loads, 2004–2009. Red lines: model results. Black dots: measurements. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4.2.2. Ecological predictions

The results of the ecological modelling showed that pH was the most important stressor (Supplementary Material, Table S3), with a strong latitudinal interaction (Fig. 8; Supplementary Material, Table S1). Generally, pH was positively related with ecological metrics, with no evident interaction with TON, as revealed by the non-significant interaction term (Supplementary Material, Table S3) and the parallel fitted lines (Fig. 8). However, at lower latitudes (red: minimum latitude, yellow: latitude Q10 and green: latitude Q50) acidity had a much lower effect on biotic metrics, compared to higher latitudes in North Wales (blue: latitude Q90, violet: maximum latitude), where reduced pH led to low values of invertebrate richness and response diversity. Increased TON values reduced only invertebrate response diversity (Fig. 8; Supplementary Material, Table S3). Environmental natural descriptors were also important. In particular, rainfall (prec_max) had a general negative influence in both biotic variables, while longitude had a negative relationship with richness. Stressors and natural descriptors explained a higher amount of variance for response diversity ($r^2 = 0.60$) relative to invertebrate richness ($r^2 = 0.51$).

The future predictions for the ecological metrics reflected different patterns. Invertebrate richness showed little variation in the future scenarios respect to control conditions (Supplementary Information, Fig. S1). Only in the Fragmented scenario invertebrate richness showed a slight reduction respect to control conditions. On the other hand, response diversity displayed different responses in relation with the longitudinal position in the river and future scenario considered (Fig. 9). The upper Wye site seemed to reflect a substantial reduction in response diversity under the Techno and Fragmented world scenarios for both 2030s and 2060s periods, which is greater in the latter scenario. However, the middle site showed a similar but less pronounced pattern of response diversity decline under Techno and Fragmented world scenarios, and an increase under the consensus world scenario for both periods. The lower Wye is expected to change little respect to current conditions under any of the scenarios considered. Despite the low magnitude of the changes in the lower Wye section, the increase in response diversity under any of the scenarios considered is remarkable.

5. Discussion

The INCA model reproduced the daily flow of the Wye effectively (Moriasi et al., 2007). The model results were more accurate for the lower stretches of the River Wye (e.g. reach 28 in Fig. 3) than for the upper reaches (e.g. reach 9 in Fig. 3), where the largest flow peaks were slightly underestimated. This is because the upper Wye is located in a mountainous area where the precipitation is potentially locally very large, especially at high elevations, but the spatial representation of the precipitation patterns through the available rain gauges in these areas is poor, mainly because the majority of the measuring stations are located at low or middle elevations. Despite this, the results of the hydrological model were satisfactory.

Figs. 4 and 5 show the results in terms of nitrate concentration and load. It can be seen that the model reproduced well the average concentrations of nitrogen at all reaches and the seasonality of the nitrogen concentration, with lower concentrations in summer and higher concentrations in winter. This behaviour is typical of the diffuse source pollutants such as nitrogen, which enters the systems via fertilisers in the agricultural areas (Whitehead et al., 1998b). This is confirmed by the average concentrations, which were relatively low in the upper reaches and higher in the middle and lower reaches, where the agricultural fraction of the catchment is higher (Supplementary Material, Table S2). The model also showed some errors in predicting the daily concentration of nitrogen. However, this is unlikely to produce any bias in the results of this study, given that these are provided in terms of long-term averages or seasonal averages, and the day-by-day variations of the nitrogen concentration are not analysed. The results in terms of nitrogen loads were clearly better than the concentration ones, due to the good results of the model in predicting the flow.

The predicted impacts of climate change on the climate of the Wye catchment were fairly similar for all models and RCPs scenarios, especially in terms of temperature. A slight increase in winter temperature is foreseen for the 2060s, although no large variations are predicted for summer temperatures. The precipitation was forecasted to decrease slightly in summer, apart from the model IPSL under RCP 4.5, which

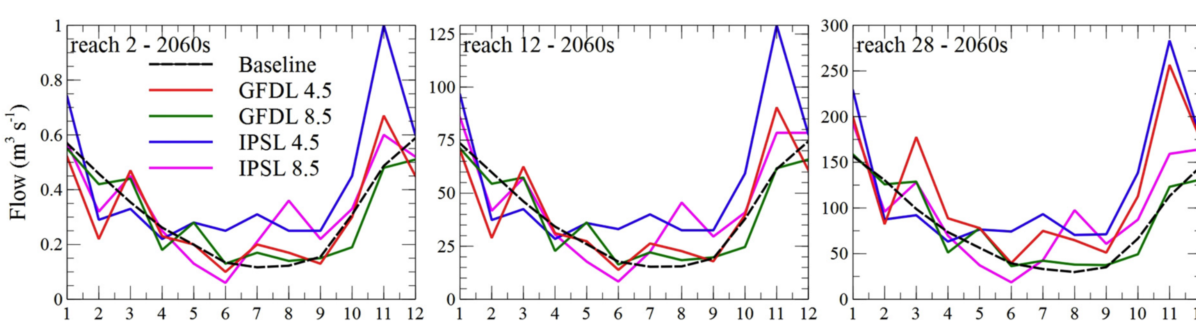

Fig. 6. Impacts of climate change on flow.

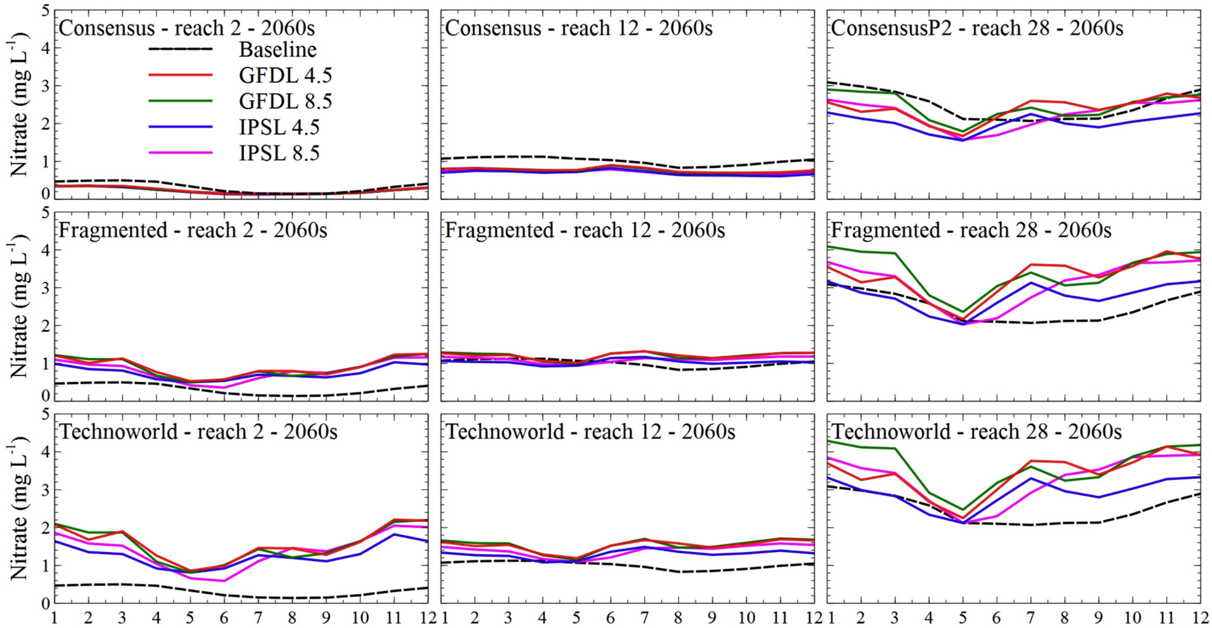

Fig. 7. Impacts of climate change and land-use change on nitrate (in nitrate-N).

predicted an increase in precipitation, especially in winter. Similar patterns were identified in other catchments in the same climatic area (Bussi et al., 2017b), although in the case of the River Wye the climate change signal on precipitation and temperature was rather weak. The effect of climate change on the flow of the river Wye is shown in Fig. 6. It shows that the flow is forecasted to increase based on the IPSL model under RCP 4.5, while the other combinations of climate model and RCP do not show very significant alterations in the flow, in agreement with the predictions shown in terms of precipitation and temperature. These results are similar to other catchments of the area (Bussi et al., 2017b), but differ from other catchments located in Southern or Eastern England, where summer flows are expected to decrease more significantly (Bussi et al., 2016a, 2016b; Guillod et al., 2018). This study therefore confirms the results of previous studies concerning the impact of climate change on flow and water quality (Whitehead et al., 2009).

The changes in nitrate concentrations due to the combined climate and land-use change are shown in Fig. 7. The key messages are: *(i)*

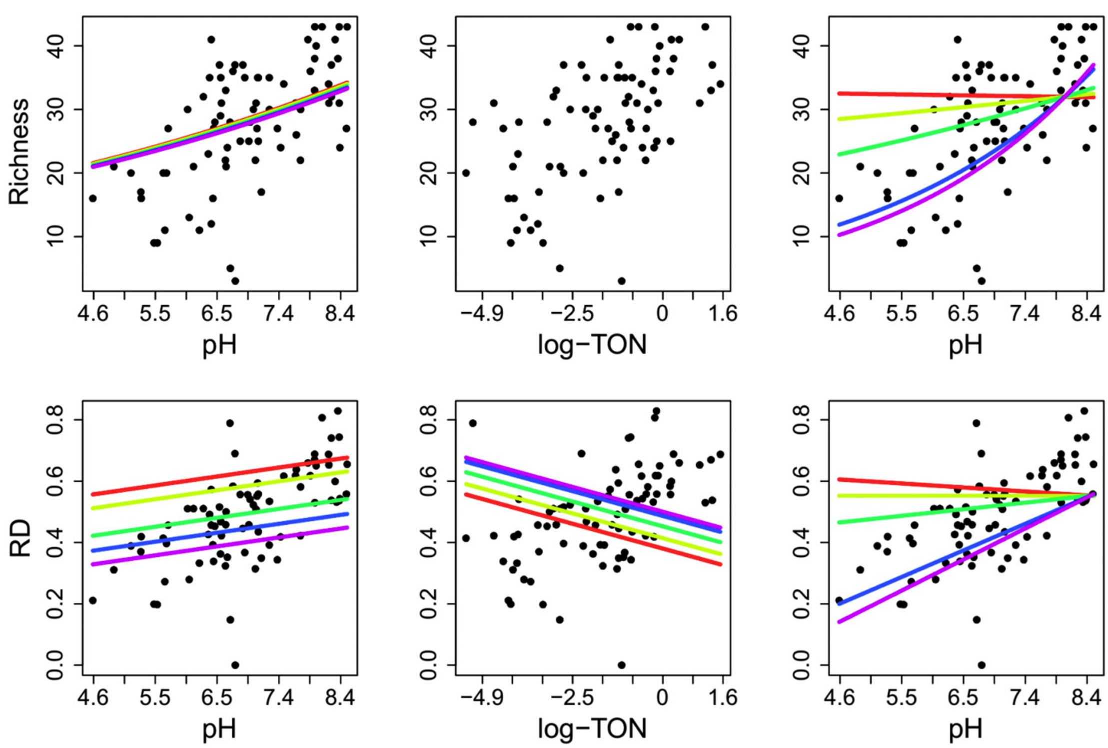

Fig. 8. Plots showing ecological responses to multi-stress. The interaction between pH and TON (a), TON and pH (b) and pH and latitude (c) are shown. Lines represent fitted values at different levels of the interacting stressor non-showed in the abscise axis (red: minimum value, yellow: Q10, green: Q50, blue: Q90 and violet: maximum value). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Climate change is unlikely to cause large variations in the upper reaches, but could lead to significant increases in nitrate concentrations in the lower reaches, due to increased runoff from agricultural areas; *(ii)* Land-use change plays a very important role in enhancing or controlling the impact of climate changes; and *(iii)* The consensus scenario is the most effective in controlling the increase of nitrate caused by climate change, due to the reduction in fertiliser use and the reduced extension of arable land. By contrast, the technoworld scenario causes an enhancement of the nitrate concentration increase due to climate change. The fragmented scenario seems not to cause large variations of nitrate concentrations for the upper and middle reaches, but it shows an increase of nitrogen in the lower reaches. No other studies were conducted on the impact of climate change on the nitrate concentration of the River Wye or rivers in the same areas to the authors' knowledge, so no comparisons can be drawn.

It is important to bear in mind that socio-economic scenarios were represented as static scenarios, i.e. they do not change along with changes in climate. This is a limitation in the representation of future changes, as climate affects land use and socio-economic development (Bussi et al., 2017a). However, this was compensated by simulating a large number of combinations between climate outcomes, land-use scenarios and socio-economic scenarios, which all span in a relatively narrow range of future conditions.

Our ecological models showed that pH is still an important anthropogenic driver of change in the Welsh uplands (Ormerod and Durance, 2009), as occurs in other poor base areas exposed to past sulphur deposition and large rainfall (Reynolds et al., 1999); (Petrin et al., 2008). Nutrients were also important, causing a reduction in response diversity. Predicted changes under future scenarios in nutrient concentration, pH, flow and climate seem to have more pronounced effects on the upper and middle parts of the River Wye, at least for response trait diversity, which reflects the importance of these variables in the ecological models. Uplands could be more sensitive to nutrient enrichment or potential acidification because they have more diverse communities composed of many pollution-intolerant species, while lowland sections are inhabited by generalist and tolerant species (e.g., Sánchez-Montoya et al., 2009). For the upper part of the Wye, our models predicted a 4-fold or 8-fold increase in nitrogen concentration under fragmented world scenario. The middle section could be also severely affected. The combination of increased nutrients and reduced pH (fragmented world) seems to affect more dramatically the diversity of response traits of the invertebrates than their taxonomic diversity. This result suggests that pollution-tolerant species could be replacing sensitive species at locations affected by high nutrient concentrations, which is reflected by changes in trait diversity. A reduced diversity of response traits could result in a less stable and resilient community (Hooper et al., 2005) and have indirect effects on the ecosystem functions and services provided by rivers (Suding et al., 2008; Woodward et al., 2012). On the other hand, the restorative land-use changes simulated for the consensus world seems to have little impact respect to the biological control conditions, despite the projected reductions in nitrogen. These results might advocate for more ambitious measures if we aim to produce a real recovery of the sites severely impacted by nutrient enrichment.

Some limitations of the applied model must be underlined. In particular, the model outcomes are affected by an uncertainty not quantified in this paper, related to the interpretation of the extreme values of nitrate concentration (occurring during the storms, mostly in the post-

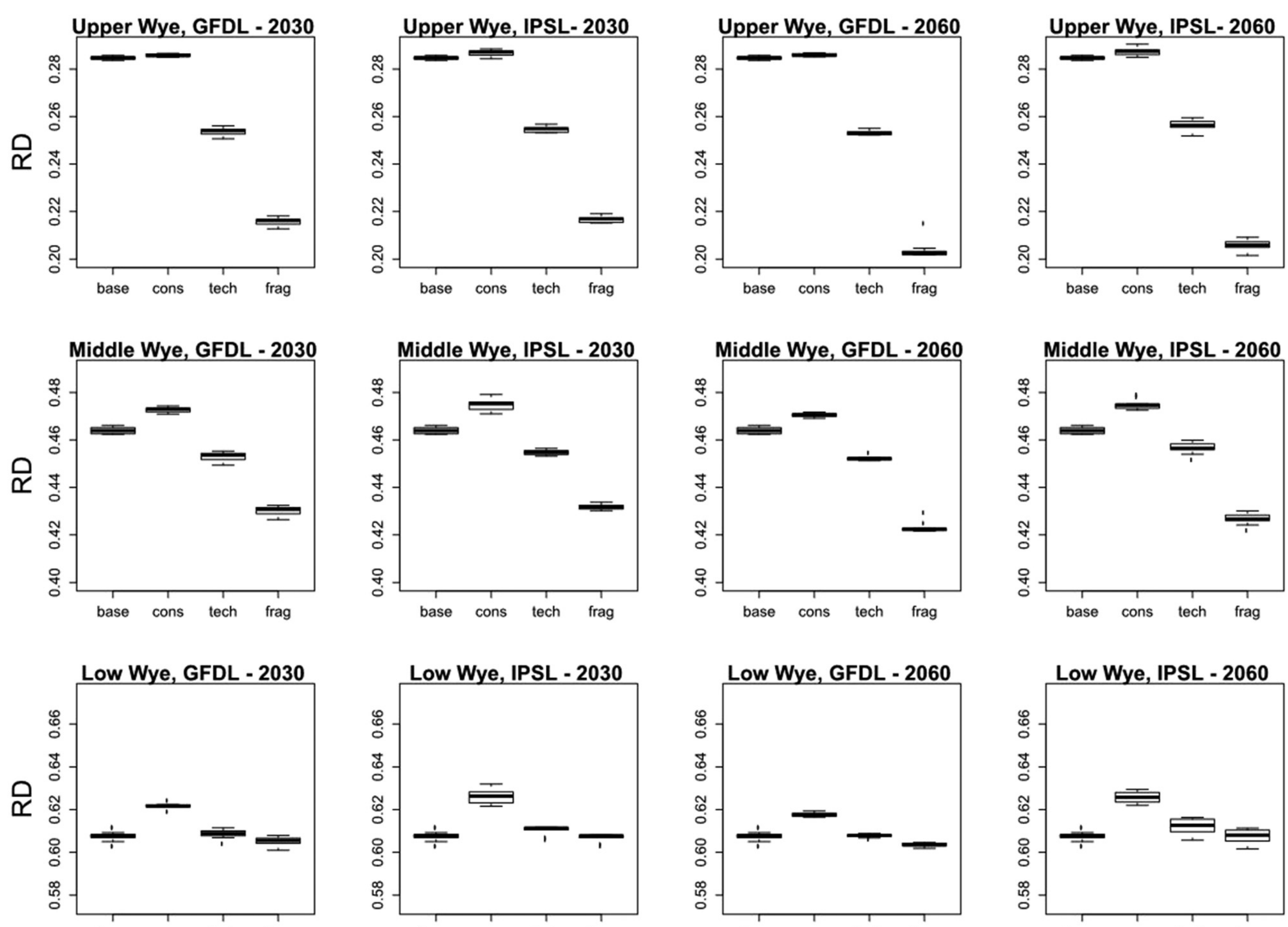

Fig. 9. Projected changes for invertebrate response diversity (RD) in the upper, middle and low Wye catchment for the baseline period (base), 2030 and 2060, and for each of the climatic models (GFDL, IPSL) and scenarios (cons: consensus world – SSP2, tech: technoworld – SSP5 and frag: fragmented world – SSP3).

summer period) and frequency of nitrate peaks (Fig. 4). However, the model outcomes in this works were used to assess changes in logn-term averages of nitrate concentrations and responses related to biological diversity and other community traits, thus the underestimation of the extremes do not invalidate the results. The addressing and modelling of the fate of nitrates and other determinants related to stress in conditions of extreme climate and hydrological conditions should be the issue of further, long-term studies.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.01.295.

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